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Dynamics of information generation and transmissions through a social network in non-recurrent transport behaviour

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Abstract

Travellers attempting to make a non-recurrent trip cannot rely on their own experiences and, consequently, must rely on information generated by others. In such situations, travellers' choices are subject to information transmissions through a social network; if this does not work well, they fail to make efficient choices owing to lack of information. This study proposes a model that describes the dynamics of information generation and transmissions and conducts an analysis to investigate the conditions that allow travellers to make efficient choices. It is shown that suppressing rapid diffusions of information and encouraging intentional searching for information can help travellers to make efficient choices.

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1. Introduction

It is important to consider how travellers obtain travel information, such as that related to destinations or routes, in order to analyse their behaviour. Travelling is an activity that takes place along a timeline, and travellers, therefore, cannot know how good their choice is before they actually travel to the selected destination. This implies that travellers must rely on some information sources in order to make a better choice.

Two information sources have been frequently discussed in transport studies. One is travellers' past experience. In most cases, travelling is a recurrent activity. A typical example is a daily commute. By making recurrent trips, travellers can try many alternatives and select the alternative that is best for them by collecting useful information through their own day-to-day experience. The other information source is an external observation system, such as the advanced traveller information system (ATIS), that does not rely on travellers' experience. Traffic information collected by loop detectors is a typical example.

Meanwhile, there are cases in which activities are not recurrent and no external observation is possible. In these cases, the experiences of other travellers become an important (and perhaps the only) information source. Two

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examples, namely, sightseeing and evacuation, are explained below.

Sightseeing is a typical case in which travellers must rely on information provided by other travellers. In general, sightseeing is a non-recurrent activity. Although the recurrent trips to the same destination made by tourists have often been discussed in existing studies owing to their importance in marketing (e.g., Oppermann, 1998), the majority of the travellers who go sightseeing are first-time visitors. For example, Oppermann (1997) showed that 68% of the visitors to New Zealand in 1993 were first-time visitors. This implies that first-time visitors still form the majority and that sightseeing is basically a non-recurrent activity. Of course, first-time visitors cannot rely on their own experience since they are visiting the place for the first time; consequently, they must rely on other information sources. Fodness and Murray (1997) classified tourist information sources into ‘guidebooks’, ‘travel agencies’, ‘newspapers’, ‘friends’, and so on. It should be noted that these sources are generated by other travellers from their past experiences; for example, guidebooks are normally written by authors who have visited the destination, and travel agencies offer tours to destinations that have been popularised by visitors who travelled to those places in the past. Newspaper articles and friends’ advice are apparently connected to someone’s experiences. It is obvious that the best (and perhaps the only) way to determine the appeal of sightseeing spots is through experience. In addition to the conventional information sources, the World Wide Web is now a major information source that directly provides details of people’s experiences. For example, many online service providers, such as web-based travel agencies (e.g., hotel booking sites), now feed guests’ opinions about hotels and other services into their systems and provide this information to future customers so that they can make decisions based on information from other travellers (Jøsang et al., 2007).

During major disasters, people encounter situations in which they cannot rely on their own past experience or on intelligent information tools. In such situations, people may use information provided by others to make decisions, even if this information is not reliable. Several studies pointed out the spread of rumours after disasters (e.g., Scanlon, 1977; Schneider, 1995; Garnett and Kouzmin, 2007), implying that inaccurate (or false) information is spread among people in these situations as a result of the lack of reliable information sources. The evacuation behaviour of occupants in a room with two exits may also be considered as a case in which people rely on others’ behaviour. Helbing et al. (2000) analysed dynamic features of escape panic using a pedestrian simulation model. In this study, the behaviour of pedestrians trying to escape a smoky room through two invisible doors is examined; this represents a panic situation in which almost all the pedestrians rush into one exit while the other exit remains empty. This phenomenon can be interpreted as a situation in which the only reliable information available to evacuees is other peoples’ behaviour (i.e., their choice of exit) that can be directly observed, leading to demand concentration at the selected exit.

In the situations mentioned above, in which only the information generated from others’ experiences is available for making a decision, it is expected that travellers are not able to make ‘efficient’ choices (i.e., choices of an alternative with higher utility), which would be possible if accurate information were available. Instead, their choices are biased towards particular alternatives in the choice set. For example, regarding sightseeing behaviour, some popular destinations are repeatedly visited by different travellers, whereas there can be many hidden sightseeing spots in the world that have not been experienced. The situation is clear when the case of the evacuation from the room with two exits—where the occupants’ choices are biased towards one exit—is considered. It should be noted that the alternative selected by travellers are determined by a small perturbation in the early stages of the travellers’ decisions, at which point only a few travellers have made decisions. In the evacuation case, the exit that is ‘randomly’ selected by the first evacuee will be the unique exit used by others.

The possible dynamics of travellers making decisions in the situation mentioned above can be roughly described as follows. Information regarding an unknown alternative (e.g., some not-so-popular sightseeing spot) is first made available only when some ‘pioneer’ happens to visit that place. Then, this information is passed on to others through social relationships. Assuming that travellers are risk averse, it can be said that they tend to visit places about which more information is available, leading to the collection of more information about those places, whereas some other places that people have not visited remain unknown. This causes the ‘enrichment of existing information in the society’. Such dynamics can result in situations in which the information about limited alternatives dominates the society while other alternatives remain unknown. Such behaviour is similar to the ‘lock-in’ phenomenon observed in technology competitions, which was investigated by Arthur (1989). As discussed in his paper, the lock-in phenomenon results in the domination of inferior technologies in society owing to externalities, such as coordination or network externalities.

On the other hand, it should be noted that the lock-in dynamics explained above can exist only under certain conditions. For example, consider a case in which the speed of information transmission is so slow that travellers are unable to obtain it before making a decision. In this case, travellers can make only random choices on account of the lack of information, and consequently, no lock-in behaviour is observed in this case. If the speed of information transmission is moderate, it can be expected that a substantial number of travellers will make decisions using a sufficient amount of information because the travellers who made random decisions in an earlier stage at which information was not widely spread out provide sufficient information on all the alternatives to other travellers. Based on these considerations, it can be expected that the decisions of travellers depend on the speed of information transmission and decision making.

While considering the speed of information transmission, the structure of information transmission networks should also be explicitly considered because information transmission paths are sometimes restricted by the geographical structure of transport networks in the context of transport behaviour studies. If transmission occurs through physical media such as direct eyesight or face-to-face chatting, the structure of information transmission networks should be similar to that of transport networks. On the other hand, if transmission occurs through social relationships, mass communication media, or the Internet, the network structure should have characteristics of social networks, such as the scale-free or small-world property. In order to generalise the model for transport behavioural issues, these differences should be explicitly investigated.

In addition to the structure of information transmission networks, the timing of information acquisition can also affect the result of travellers' choices. Two modes of information transmission have been pointed out in the literature on information search behaviour (e.g., Gursoy and McCleary, 2004; Peterson and Merion, 2003). One mode is the intentional search that is undertaken only when a traveller demands more information for making a choice. The other mode is the incidental diffusion of information that can happen at any time. It can occur during various activities, such as chatting with others or surfing the Internet. While incidental diffusion can happen at any time, intentional searches can be carried out only when people attempt to make a choice. Moreover, it is made only when the cost of the search is inexpensive compared to the expected benefit of searching. These two different modes of information transmission can occur at different timings, and this can affect the speed of information transmission.

This study determines the conditions that cause the lock-in behaviour in the system and the optimal conditions that allow travellers to obtain sufficient information for making efficient choices. The following three parameters are investigated in this study: (1) the speed of information transmission, (2) the structure of the information transmission network, and (3) the timing of information acquisition. This paper consists of five sections, including this introduction section. In Section 2, the model of information transmission and travellers' behaviour is developed. Mathematical analyses of the model are performed in Section 3, which reveals the conditions that aid travellers in making efficient choices. Section 4 presents numerical examples, and Section 5 contains the conclusions and discussions. Section 5 also includes a few implications of the model in the real world.

2. Model

This study performs a theoretical analysis of non-recurrent choice behaviour of travellers who are connected by a network that transmits information from one to another. To facilitate the analysis, the following assumptions are made throughout the paper:

1 **System components:** The system considered in this study, referred to as 'the society', consists of travellers and alternatives (such as destinations or routes) that will be selected by travellers. A traveller is an individual who attempts to select an alternative only once to make a non-recurrent trip. The set of travellers is denoted by N, and the set of alternatives (i.e., the travellers' choice set) is denoted by A. The number of travellers is denoted by n. To simplify the problem, only the binomial choice is considered in this study. The choice set is denoted by $A = (H, L)$, where H and L are alternatives available to all users.

2 **Dynamic system:** The state of the society changes over time. The period of time considered is denoted by $T = [0, \infty)$. The scale of the time can vary depending on the problem settings; it can be seconds if the situation changes rapidly, but it can also be years if the long-term change is the concern of the analysis.

3 **Utility of alternatives:** Each alternative is associated with its utility, which is denoted by $v_c > 0$, where $c \in A$. The utility of each alternative is the same for all travellers. Without loss of generality, it is assumed that the utility of alternative *H* is higher than that of *L*, i.e., $v_H > v_L$.

4 **Amount of information:** Each traveller has information on each alternative. The amount of information on each alternative is denoted by $a(i,c,t) \geq 0$, where $i \in N, c \in A,$ and $t \in T$. No traveller has information at the initial time (i.e., $t = 0$), that is, $a(i,c,0) = 0$ for $i \in N$ and $c \in A$.

5 **Timings of decisions:** Each traveller selects an alternative only once at time $\tau(i)$, where $i \in N$. The travellers' decision timings $\tau(i)$ follow the uniform distribution between 0 and *n*/*r*, where *r* is the number of travellers selecting the alternative per unit time (i.e., the speed of decision making).

6 **Choices under imperfect information:** Travellers are risk averse and therefore tend to avoid selecting an alternative if they have poor information on it. The utility of alternative $c \in A$ that is perceived by travellers is calculated as a simple multiplication of the utility and the amount of information, that is, $v_c a(i,c,\tau(i))$. The value $v_c a(i,c,\tau(i))$ is referred to as 'perceived utility'. Travellers' choice behaviour is described by the binomial logit model. The alternative that traveller i selects is denoted by $c(i)$.

7 **Information acquirement:** Each traveller performs the activity associated with his or her selected alternative immediately after the decision. Then, he or she acquires information on the selected alternative. The amount of information obtained is identical for any alternative and is assumed to be 1. This is the only source of information; no other information source exists in the society.

8 **Information transmission network:** Information is transmitted only via an information transmission network. A set of travellers directly connected to traveller $i \in N$ by a link is denoted by $N(i)$. The travellers in set $N(i)$ are referred to as the neighbour travellers of traveller *i*.

9 **Additivity of information:** Information acquired by different travellers is not identical and does not overlap. Therefore, if traveller i receives information that originates from traveller j and k, the total amount of information that traveller i receives is 2 if and only if $j \neq k$, which implies that the amount of information $a(i,c,t)$ indicates the number of travellers whose information is transmitted to traveller *i* until time *t*. If a traveller receives information acquired by the same traveller two or more times, the amount of information does not increase at all.

10 **Incidental diffusion of information:** Information that is kept by a traveller is diffused to neighbour travellers. This transmission happens frequently in daily life, such as when chatting with others or surfing the Internet. The occurrence rate of transmissions per unit time is constant and identical for all links. The rate is denoted by γ.

11 **Intentional search for information:** If (and only if) a traveller has the intention to search for more information, he or she attempts to collect additional information from all neighbour travellers just before making the decision. Whether the intentional searches are performed by travellers depends on the expected costs and benefits of the searching. For simplicity, this study considers two extreme cases only, that is, a case in which searching costs are so expensive that no one is willing to make any intentional search, and a case in which the searching cost is so low that every traveller performs the intentional search before making a decision. Variable δ_{IS} is used to describe which case is applicable—$\delta_{IS} = 1$ if the intentional search is on; otherwise, $\delta_{IS} = 0$.

The final goal of the analysis is to know how many travellers can select alternative *H* rather than *L* based on certain values of parameters v_H, v_L, r, γ, and δ_{IS} and on the structure of the network described by $N(i)$. The term *efficient choices* is used in this paper to refer to all travellers' final choices consisting of 50% or more *H*. To evaluate whether travellers can make efficient choices in the final state, one should calculate the results of all travellers' choices (i.e., $c(i)$ for $\forall i \in N$) that are determined by the dynamics defined above.

Prior to constructing an equation system for finding the result, the calculation procedure of the incidental diffusion of information is examined. From Assumption 7, any information transmitted by the incidental diffusion originates at a certain traveller. Let $a_j^D(i,c,t)$ be the amount of information that originates at traveller $j \in N$ and is transmitted only by incidental diffusions. Then, consider how $a_j^D(i,c,t)$ will be calculated. From Assumption 9, the value of $a_j^D(i,c,t)$ changes only when traveller *i* receives information acquired by traveller j for the first time because receiving the same information more than once does not contribute to the increase of the amount of information. From this consideration, it can be concluded that information originating at a certain traveller diffuses to other travellers via a shortest path, and any other paths can be neglected in the calculation of $a_j^D(i,c,t)$. Therefore,

$$a_j^D(i,c,t) = \delta(c(j),c)\theta(t-\tau(j)-d(i,j)/\gamma), \tag{1}$$

where $\delta(b,c)$ is the Kronecker delta (i.e., $\delta(b,c)$ is 1 if $b=c$, otherwise 0), $\theta(x)$ is the unit step function (i.e., $\theta(x)$ is 1 if $x \geq 0$, otherwise 0), and $d(i,j)$ is the number of links in a shortest path between travellers i and j in the information transmission network (note that 'shortest' means 'smallest number of links in a path' in this definition). In the following descriptions, the number of links in a shortest path between two travellers is simply denoted by 'distance'.

Information acquired by the intentional search is also determined. Let $a_j^{IS}(i,c)$ be the amount of information of alternative c originating from traveller j and taken by traveller i 's intentional search. It can be written as:

$$a_j^{IS}(i,c) = \max_{k \in N(i)}\left[\max\left\{a_j^D(k,c,\tau(i)), \theta(\tau(i)-\tau(k))a_j^{IS}(k,c)\right\}\right]. \tag{2}$$

With Eqns. (1) and (2) in hand, an equation system can be derived from the assumptions shown, as follows:

$$\tau(i) \sim U(0,n/r) \quad \text{for } i \in N \tag{3}$$

$$\Pr(c(i)=c) = \frac{\exp\left[v_c \sum_{j \in N} \max\left\{a_j^D(i,c,\tau(i)), \delta_{IS} a_j^{IS}(i,c)\right\}\right]}{\sum_{b \in A} \exp\left[v_b \sum_{j \in N} \max\left\{a_j^D(i,b,\tau(i)), \delta_{IS} a_j^{IS}(i,b)\right\}\right]} \quad \text{for } i \in N. \tag{4}$$

When $\delta_{IS} = 0$, Eqn. (4) becomes simpler as follows:

$$\Pr(c(i)=c) = \frac{\exp\left[v_c a(i,c,\tau(i))\right]}{\sum_{b \in A} \exp\left[v_b a(i,b,\tau(i))\right]} \quad \text{for } i \in N, \tag{5}$$

where

$$a(i,c,t) = \sum_{j \in N} \delta(c(j),c)\theta(t-\tau(j)-d(i,j)/\gamma). \tag{6}$$

Eqn. (3) defines the timing when each traveller makes the decision, whereas Eqn. (4) or (5) defines the choice probability of each alternative under a certain amount of information that traveller i has at the time of the decision. Eqn. (6) describes how information diffuses across the network when $\delta_{IS} = 0$.

This equation system includes stochastic procedures and, consequently, $c(i)$ is a random variable. To perform a naïve Monte Carlo method that estimates the probabilistic distribution of $c(i)$, the values of $\tau(i)$ are firstly sampled by Eqn. (3). Then, the time-dependent stochastic process defined by Eqn. (4) is performed from $t=0$ until all travellers select destinations (i.e., $t = \max_{i \in N} \tau(i)$). After running this process, the number of travellers that selected destination H is counted. By repeating this sampling method many times, the distribution of the number of travellers selecting H can be numerically calculated. On the other hand, one can also apply the continuous approximation to estimate the mathematical behaviour of the model output without performing the Monte Carlo method. This will be demonstrated in the next section.

3. Mathematical analysis of the proposed model

Mathematical characteristics of the equation system proposed in the last section are examined in this section. In this section, to facilitate the mathematical analysis, it is assumed that the number of travellers is so large that continuous approximation can be applied to describe the number of travellers. The simplest case, in which information is rapidly diffused once it is generated in the network, is firstly examined in the next subsection, and this is followed by the analysis of general cases.

3.1. Rapid diffusion of information

The mathematical analysis of the proposed model is simple when we assume that information spreads out to all travellers immediately after it is generated. This assumption implies $\gamma \to \infty$, which leads to

$$a(i,c,t) = \sum_{j \in N} \delta(c(j),c)\theta\left(t - \tau(j)\right) \tag{7}$$

instead of Eqn. (6). In addition, because any information is known by all travellers immediately after its generation, the intentional search never increases the amount of information; consequently, the effect of $a^{IS}(i,c,t)$ does not have to be considered. Note that Eqn. (7) does not contain any variable that depends on the network structure, such as $d(i,j)$ or $N(i)$, implying that the following analysis is applicable to any type of network. Further, because the amount of information is identical for all travellers, the argument i can be omitted from $a(i,c,t)$. Therefore, we let

$$h(t) = a(i,H,t) \text{ and } l(t) = a(i,L,t) \quad \text{for } i \in N, \tag{8}$$

where $h(t)$ and $l(t)$ denote the numbers of travellers who have selected alternative H and L until time t, respectively.

Applying the continuous approximation, we obtain the following differential equation system:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{r}{1 + \exp\left\{v_L l(t) - v_H h(t)\right\}} \tag{9}$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{r}{1 + \exp\left\{v_H h(t) - v_L l(t)\right\}} \tag{10}$$

for $0 \le t \le n/r$, where n is the number of travellers. For $t > n/r$, both $h(t)$ and $l(t)$ remain unchanged because all travellers have already selected one of the alternatives before time n/r. This is an initial-value problem whose initial conditions are $h(0) = l(0) = 0$. Note that any stochastic effect in the original model can be neglected on account of the continuous approximation. As shown in Fig. 1, a piecewise linear approximation of the nonlinear term on the right-hand side of Eqns. (9) and (10) is introduced to calculate its integration analytically. First, Eqns. (9) and (10) are replaced by

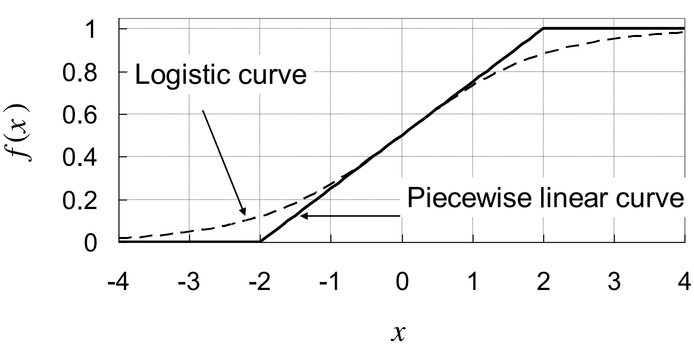

Fig. 1: Piecewise approximation of the logistic curve.

$$\frac{\mathrm{d}h}{\mathrm{d}t} = rf\left(\Delta(t)\right) \tag{11}$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = rf\left(-\Delta(t)\right), \tag{12}$$

where

$$\Delta(t) = v_H h(t) - v_L l(t) \tag{13}$$

and

$$f(x) = \max\left\{0, \min\left\{\frac{x}{4} + \frac{1}{2}, 1\right\}\right\}, \tag{14}$$

which is the piecewise linear approximation of the logistic curve. Because $\Delta(t) = 0$,

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{r}{4}\Delta(t) + \frac{r}{2} \tag{15}$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = -\frac{r}{4}\Delta(t) + \frac{r}{2} \tag{16}$$

is applicable from $t = 0$ until $\Delta(t)$ reaches 2 or -2 or $t = n/r$. Once $\Delta(t) = 2$ is established at $t = t_S$, the right-hand side of Eqn. (11) and Eqn. (12) is r and 0, respectively, and consequently $h(t) - h(t_S) = r(t - t_S)$ and $l(t) = l(t_S)$ for $t_S \le t \le n/r$ (if $t_S \le n/r$). Similarly, once $\Delta(t) = -2$ is established at $t = t_S$, the right-hand side of Eqn. (11) and Eqn. (12) is 0 and r, respectively; consequently, $h(t) = h(t_S)$ and $l(t) - l(t_S) = r(t - t_S)$ for $t_S \le t \le n/r$. These behaviours of the differential equation system lead to an important characteristic—once $\Delta(t)$ reaches 2 or -2, the alternative whose population (weighted by v_H or v_L) is less will no longer be selected, and all the travellers who have not made decisions will select the other alternative. t_S is referred to as the ‘saturation timing’.

From Eqns. (15) and (16), a differential equation of $\Delta(t)$ from $t = 0$ until $\Delta(t) = 2$ or -2 is obtained as follows:

$$\frac{\mathrm{d}\Delta}{\mathrm{d}t} = \frac{v_+ r}{4}\Delta(t) + \frac{v_- r}{2}, \tag{17}$$

where $v_+ = v_H + v_L$ and $v_- = v_H - v_L$. Eqn. (17) is a typical inhomogeneous first-order linear ordinary differential equation. Its general solution is

$$\Delta(t) = C\exp\left(\frac{v_+}{4}rt\right) - \frac{2v_-}{v_+} \tag{18}$$

for $0 \le t \le \min\{t_S, n/r\}$, where C is a constant. If the initial condition is $h(0) = l(0) = 0$, $\Delta(0) = 0$, and consequently

$$\Delta(t) = \frac{2v_-}{v_+}\left(\exp\left(\frac{v_+}{4}rt\right) - 1\right) \tag{19}$$

is obtained for $0 \le t \le \min\{t_S, n/r\}$. Note that $\Delta(t)$ is always positive because $v_- > 0$. t_S can be calculated by solving the equation $\Delta(t_S) = 2$, and the corresponding solution is

$$t_S = \frac{4}{rv_+}\ln\left\{\frac{v_+}{v_-} + 1\right\}. \tag{20}$$

Because the total number of travellers selecting either alternative (i.e., $h(t) + l(t)$) increases at rate r ,

$$h(t) + l(t) = rt \tag{21}$$

for $0 \le t \le n/r$. Solving (21) and (19) for *h*(*t*) and *l*(*t*), we obtain

$$h(t) = \frac{v_L}{v_+} rt + \frac{2v_-}{v_+^2}\left(\exp\left(\frac{v_+}{4} rt\right) - 1\right) \tag{22}$$

$$l(t) = \frac{v_H}{v_+} rt - \frac{2v_-}{v_+^2}\left(\exp\left(\frac{v_+}{4} rt\right) - 1\right) \tag{23}$$

for $0 \le t \le \min\{t_S, n/r\}$. Therefore,

$$l(t_S) = \frac{1}{v_+}\left\{\frac{4v_H}{v_+}\ln\left(\frac{v_+}{v_-} + 1\right) - 2\right\} \tag{24}$$

if $t_S \le n/r$. Note that $l(t_S)$ indicates the total number of travellers who select *L* during the dynamics, implying that most travellers can successfully select *H* if $l(t_S)$ is much smaller than *n*.

From Eqn. (24) and a relationship between a linear function and a logarithm function, i.e., $\ln(x+1) \le x$ for *x* with $x \ge 0$, we obtain the following inequality:

$$l(t_S) = \frac{1}{v_+}\left\{\frac{4v_H}{v_+}\ln\left(\frac{v_+}{v_-} + 1\right) - 2\right\} \le \frac{1}{v_+}\left\{\frac{4v_H}{v_-} - 2\right\} < \frac{4}{v_H - v_L}. \tag{25}$$

Therefore, if the difference of v_H and v_L is greater than 1, it can be concluded that only a few travellers select *L*, implying that almost all travellers successfully select *H*.

However, it should be pointed out that the solution shown in Eqns. (22) and (23) may not be stable against small perturbations of the initial condition. We will consider another initial condition— $h(\varepsilon/r) = 0$ and $l(\varepsilon/r) = \varepsilon$ ($0 < \varepsilon \ll n$)—to evaluate the effect of the perturbation (this setting means that all travellers select *L* between time 0 and ε/r). In this case, $\Delta(\varepsilon/r) = -v_L\varepsilon$, and consequently,

$$\Delta(t) = \left(\frac{2v_-}{v_+} - v_L\varepsilon\right)\exp\left(\frac{v_+}{4} r\left(t - \varepsilon/r\right)\right) - \frac{2v_-}{v_+} \text{ for } t \text{ with } t \ge \varepsilon/r \tag{26}$$

is obtained instead of Eqn. (19), implying that the sign of $\Delta(t)$ will take a negative value when $\varepsilon > 2v_-/v_Lv_+$ and will become −2 at a certain time. This is the exact opposite of the solution that is derived from the initial condition $\Delta(0) = 0$—in the solution of Eqn. (26), if $\varepsilon > 2v_-/v_Lv_+$, the number of travellers selecting *H* will not change after the saturation timing, whereas the number of travellers selecting *L* will increase until all the travellers have made decisions. As the value of threshold $2v_-/v_Lv_+$ is smaller than $2/v_L$, $\varepsilon = 1$ is sufficient for this phenomenon if $v_L > 2$.

As the calculation is based on the continuous approximation, the small perturbation whose value is around 1 is likely to exist. This depends on which alternative is chosen by the 'pioneer' who makes the first decision—if he or she selects *L* (and $v_L > 2$, implying that people perceive a certain amount of utility in *L*, which can be nevertheless far smaller than that of *H*), ε becomes 1, and almost all other travellers will also select *L*. This leads to a situation in which the better alternative is not selected because information on the inferior alternative dominates the society. This phenomenon can be interpreted as lock-in behaviour of information.

The lock-in behaviour seems to be caused by the rapid diffusion of information; when the information introduced into the society by the pioneer is related to the inferior alternative, this information quickly spreads out before someone else finds the superior alternative, and people have no chance to select it. Such a mechanism may not become established when the diffusion speed of the information is slower. The next subsection will expand the analysis to the case in which γ has a finite value.

3.2. Slower diffusions of information without intentional search

This subsection analyses a case in which γ is finite and no intentional search is made at the time of the decisions (i.e., $\delta_{IS} = 0$). In this case, travellers are no longer identical because $d(i, j)$ cannot be eliminated from Eqn. (6).

The mean field approximation is employed to perform the analytical approach to this case. First, let $\bar{a}(c,t)$ be the mean value of the information amount, that is,

$$\bar{a}(c,t) = \frac{1}{n}\sum_{i\in N} a(i,c,t)\ . \tag{27}$$

The continuous approximation is also employed in the following analysis. Unless otherwise stated, all the notations in the previous section are still applicable.

It is assumed that the society consists of n average travellers, whose choice behaviour is determined as if they possess the average amount of information on the alternatives. From this assumption, a differential equation system can be constructed as follows:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = \frac{r}{1+\exp\left\{v_L\bar{a}(L,t) - v_H\bar{a}(H,t)\right\}} \tag{28}$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{r}{1+\exp\left\{v_H\bar{a}(H,t) - v_L\bar{a}(L,t)\right\}}\ , \tag{29}$$

where $h(t)$ and $l(t)$ are the numbers of travellers selecting H and L, respectively. Introducing the piecewise linear approximation of the logistic curve in the manner of Section 3.1, Eqns. (28) and (29) can be replaced by

$$\frac{\mathrm{d}h}{\mathrm{d}t} = rf\left(v_H\bar{a}(H,t) - v_L\bar{a}(L,t)\right) \tag{30}$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = rf\left(-v_H\bar{a}(H,t) + v_L\bar{a}(L,t)\right). \tag{31}$$

Although the detailed characteristics of information transmission depend on the structure of the information transmission network, the most important thing is that information is transmitted to each traveller with a certain delay since its generation. Therefore, the expression of

$$\bar{a}(H,t) = \begin{cases} 0 & \text{if } t < u \\ h(t-u) & \text{if } t \geq u \end{cases}, \tag{32}$$

$$\bar{a}(L,t) = \begin{cases} 0 & \text{if } t < u \\ l(t-u) & \text{if } t \geq u \end{cases}, \tag{33}$$

where $\bar{d}$ is the mean distance between two arbitrary travellers and $u = \bar{d}/\gamma$ (i.e., the travel time of information for the mean distance), should be suitable to incorporate the effect of the delay into the equation system using the simplest form. Substituting (32) and (33) into (30) and (31), we obtain a delay differential equations as follows:

$$\frac{\mathrm{d}h}{\mathrm{d}t} = rf\left(\Delta(t-u)\right), \tag{34}$$

$$\frac{\mathrm{d}l}{\mathrm{d}t} = rf\left(-\Delta(t-u)\right). \tag{35}$$

Similar to the analysis in Section 3.1, to consider the effect of small perturbations, let $h(\varepsilon / r) = 0$ and $l(\varepsilon / r) = \varepsilon$ ($0 < \varepsilon \ll n$). Then, by letting $\Delta(t) = 0$ for t with $-\infty < t \leq \varepsilon / r$, the solution of (34) and (35) for t with $\varepsilon / r \leq t \leq \min\{u + \varepsilon / r, n / r\}$ becomes

$$h(t)=\frac{1}{2}rt-\frac{\varepsilon}{2},\ l(t)=\frac{1}{2}rt+\frac{\varepsilon}{2} \tag{36}$$

because $f(0)=1/2$. From Eqn. (36),

$$\Delta(t)=\frac{v_{-}rt}{2}-\frac{v_{+}\varepsilon}{2} \tag{37}$$

is obtained for t with $\varepsilon/r\le t\le \min\{u+\varepsilon/r, n/r\}$. If $n/r\le u+\varepsilon/r$, all travellers select H or L before time $u+\varepsilon/r$, and consequently, the final solution of $h(t)$ and $l(t)$ for $t\ge n/r$ is

$$h(t)=\frac{n-\varepsilon}{2},\ l(t)=\frac{n+\varepsilon}{2}, \tag{38}$$

which implies that travellers do not make efficient choices—rather, they make random choices regardless of the utility v_H and v_L of the alternatives. Meanwhile, if $u+\varepsilon/r<n/r$, $h(t)$ and $l(t)$ are

$$h(t)=h\left(u+\frac{\varepsilon}{r}\right)+\int_{\varepsilon/r}^{t-u} rf\left(\frac{v_{-}rs}{2}-\frac{v_{+}\varepsilon}{2}\right)ds, \tag{39}$$

$$l(t)=l\left(u+\frac{\varepsilon}{r}\right)+\int_{\varepsilon/r}^{t-u} rf\left(\frac{v_{+}\varepsilon}{2}-\frac{v_{-}rs}{2}\right)ds, \tag{40}$$

for t with $u+\varepsilon/r\le t\le \min\{2u+\varepsilon/r, n/r\}$, respectively, and, $h(t)>l(t)-\varepsilon$ is satisfied if and only if

$$\frac{v_{+}\varepsilon}{2}-\frac{v_{-}\varepsilon}{2}<\frac{v_{-}r(t-u)}{2}-\frac{v_{+}\varepsilon}{2} \tag{41}$$

holds. Eqn. (41) is identical to:

$$\left(1-\frac{2v_{+}}{v_{-}}\right)\frac{\varepsilon}{r}+t>u. \tag{42}$$

Therefore, if $u+\varepsilon/r<n/r\le 2u+\varepsilon/r,$ the condition for efficient choices is as follows (note that, because $\varepsilon \ll n$, $h(n/r)>l(n/r)+\varepsilon$ is approximately identical to $h(n/r)>l(n/r)$):

$$\left(1-\frac{2v_{+}}{v_{-}}\right)\varepsilon+n>ru. \tag{43}$$

If $n/r>2u+\varepsilon/r$, $\Delta(t)$ for t with $t>u+\varepsilon/r$ should be calculated, which can be obtained by solving

$$\frac{\mathrm{d}\Delta}{\mathrm{d}t}=\frac{v_{+}r}{4}\Delta(t-u)+\frac{v_{-}r}{2}. \tag{44}$$

Eqn. (44) is a delay differential equation derived from Eqns. (34) and (35) (note that it is valid for $|\Delta(t-u)|\le 2$). Its solution can be solved by calculating the definite integration repeatedly between $t=iu+\varepsilon/r$ and $t=(i+1)u+\varepsilon/r$ for integer $i\ge 0$. Using Eqn. (37) for the initial solution till $t=u+\varepsilon/r$,

$$\Delta(t)\approx \zeta q^{(t-\varepsilon/r)/u-1}-\frac{2v_{-}}{v_{+}} \tag{45}$$

where

$$q = \left(\frac{v_+ ru}{4} + 1 \right), \tag{46}$$

$$\zeta = \frac{2v_-}{v_+} + \left(\frac{v_- ru}{2} - v_L \varepsilon \right) \tag{47}$$

is obtained for t with $u + \varepsilon / r \le t \le n / r$ and $|\Delta(t-u)| \le 2$ as an approximated solution (see Appendix A for details). Once $|\Delta(t-u)| = 2$, the alternative whose population (weighted by v_H or v_L) is lower will no longer be selected and all the travellers who have not made decisions will select the other alternative.

Consider the condition for the efficient choices for the case of $n / r > 2u + \varepsilon / r$. First, assume that $h(2u + \varepsilon / r) > l(2u + \varepsilon / r) - \varepsilon$. Given Eqn. (42), this condition is identical to

$$ru > \frac{4 v_L \varepsilon}{v_-}. \tag{48}$$

If Eqn. (48) holds and the increase of $h(t)$ is greater than that of $l(t)$ for t with $2u + \varepsilon / r \le t \le n / r$, travellers make efficient choices (recall $\varepsilon \ll n$). Given Eqns. (34) and (35), the increase of $h(t)$ is greater than that of $l(t)$ if and only if $\Delta(t-u) > 0$. Given Eqn. (45), $\Delta(t-u) > 0$ for t with $2u + \varepsilon / r \le t \le n / r$ if and only if $\zeta > 2v_- / v_+$ (note that $q > 1$), which derives

$$ru > \frac{2 v_L \varepsilon}{v_-}. \tag{49}$$

Note that (49) is always established once (48) is established. Next, consider the case of $\Delta(u + \varepsilon / r) > 2$ (note that Eqn. (48) is not assumed in this case). In this case, all travellers select H for t with $2u + \varepsilon / r \le t \le n / r$, and consequently

$$h\left(\frac{n}{r} \right) \ge \left(\frac{1}{2} ru + \frac{\varepsilon}{2} \right) + \left(n - 2ru - \varepsilon \right) = n - \frac{3}{2} ru - \frac{1}{2} \varepsilon. \tag{50}$$

Therefore,

$$n - \frac{3}{2} ru - \frac{1}{2} \varepsilon > \frac{1}{2} n \;\text{ and }\; \Delta(u + \varepsilon / r) > 2 \tag{51}$$

is a sufficient condition for travellers to make efficient choices. The first inequality of Eqn. (51) can be replaced by $n / r > 3u$ by applying $\varepsilon \ll n$, while the second inequality can be rewritten as:

$$\frac{2 v_L \varepsilon + 4}{v_-} < ru. \tag{52}$$

All the conditions shown above are summarised as follows (note that $ru < n$ (i.e., $1/n < 1/ru$) is mandatory at any time for the efficient choices).

Condition 1: For $1/n < 1/ru \le 2/n$, travellers make efficient choices if and only if Eqn. (43) holds.
Condition 2: For $2/n < 1/ru \le 3/n$, travellers make efficient choices if Eqn. (48) holds.
Condition 3: For $3/n < 1/ru$, travellers make efficient choices if Eqn. (52) holds.

Note that, in these conditions, $\varepsilon \ll n$ has been already applied for simplification. Because Eqn. (52) defines the lower limit of ru (i.e., the upper limit of $1/ru$), the conditions shown above determines a bounded region of $1/ru$ in which the efficient choices are guaranteed. This result implies the following proposition:

Proposition 1: The range of information diffusion speed for making efficient choices

If the ratio of the information diffusion speed to the decision-making speed is within a certain range defined by the number of travellers, the utilities, and the expected small perturbations, travellers will make efficient choices. Otherwise, travellers will make random choices (if the information diffusion speed is slower) or will be locked in one of the alternatives randomly (if the information diffusion speed is faster).

Note that $1/u$ ($=\gamma/\bar{d}$) indicates the information diffusion speed (i.e., how fast the information travels through the average distance of the network) and therefore $1/ru$ is equal to the ratio of the information diffusion speed to the decision-making speed. As the value of the small perturbations cannot be explicitly defined, the range determined above is not precise. However, letting $\varepsilon = 1$ seems to be adequate because it corresponds to a perturbation made by a pioneer who makes the first decision. An example of how to calculate the range will be shown in Section 4.

3.3. Effect of intentional information searches

The preceding analysis did not consider the effect of intentional information searching, but it is likely that such searching is performed often by travellers who attempt to make non-recurrent decisions. However, mathematical analysis of the intentional searching is difficult because a simple calculation, such as that shown in Eqn. (6) for the incidental information diffusion, is not available for the intentional search. This subsection discusses the qualitative effects of the intentional information searching to aid in evaluating its effect.

To examine how information is transmitted by the intentional searches, consider a simple information transmission network, as depicted in Fig. 2. Eqn. (2) implies that $a_j^{IS}(i,c)$ is information collected from neighbours $k \in N(i)$ at time $\tau(i)$. As this transmission occurs only when the decision is made, information obtained by traveller A is transmitted to traveller C only when the order of the decision making is 'A, B, and C'. If the time sequence of their choices follows this order, traveller B gets information from A by his or her own intentional search, and traveller C gets information from B, who already possesses information that originated at traveller A. On the other hand, if other orders are realised, the transmission is disconnected before arriving at traveller C. Therefore, the probability that the information originating from A will be passed to C is $1/3! = 1/6$. If the number of nodes is n and the network configuration is that of Fig. 3, the probability will be $1/n! \approx (n/e)^{-n}$, the value of which will be quite small if n is large (e.g., 1/100! $\approx$ 10^{-158}).

The above consideration implies that information transmitted by intentional searches does not reach travellers who are located in the more distance areas of the information transmission network. Accordingly, if $\bar{d}$ is much greater than 1, information does not diffuse through the entire network but only within the local neighbours of the information source, if only the intentional search is available. On the other hand, if $\bar{d}$ □ 1, the intentional search can have an effect that is the same as that of incidental information diffusion. Because the number of the links that transmit information during each intentional search is the same as the number of neighbour travellers, the speed of the information transmissions made by intentional searches corresponds to the speed of the incidental information diffusions, where $\gamma \approx r\bar{N}$ ($\bar{N}$ is the average number of neighbours, that is, $\bar{N} = 1/n\sum_{i \in N}|N(i)|$).

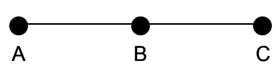

Fig. 2: Linear information transmission network consisting of three nodes.

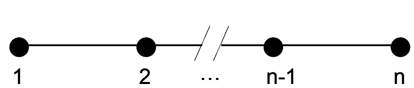

Fig. 3: Linear information transmission network consisting of *n* nodes

It should be pointed out that if $\bar{d} \simeq 1$ and $\bar{N}$ is not so large (say, $\mathrm{Ord}(\bar{N}) = 1$), the speed of information transmissions resulting from the intentional search satisfies $1/n < 1/ru$ because $1/u = \gamma / \bar{d} \approx r\bar{N} / \bar{d} \approx r \gg r/n$. This result implies that the intentional search helps travellers to make efficient choices if the incidental information diffusion is not available or is very slow, such that $1/n < 1/ru$ is not satisfied. In other words, if the intentional search is available for travellers and the network satisfies certain conditions discussed above, a good policy for allowing people to select the better alternative can be ‘suppressing the faster incidental information diffusion’, which can interfere the ‘lock-in’ phenomenon into one of the alternatives. To conclude this consideration, the following proposition is stated.

Proposition 2: Effect of intentional searching

If no faster incidental diffusion of information exists, the mean distance of the network is near 1, and the mean number of neighbour travellers is not large, intentional searching helps travellers to make efficient choices.

The analysis in this subsection is only performed in a qualitative manner. To confirm the above proposition, numerical calculations will be made in Section 4.

3.4. Effects of network structure

The above analyses assumed a few indices of the information transmission network, such as the mean distance between two arbitrary travellers (denoted by $\bar{d}$) and the mean number of neighbour travellers (denoted by $\bar{N}$), to estimate the behaviour of the dynamics. The properties of these indices representing the network structure have been extensively investigated in the area of social network analysis. This study employs the findings in the literature to determine the indices.

Two types of network structure can be considered for the information transmission networks. One is a ‘physical network’, which represents information transmission via physical media such as direct eyesight, sounds, or face-to-face chatting with neighbours. This type of network is often related to transport networks—people can meet up with other people by travelling through a transport network. These media of information transmission may be dominant during a major disaster in which information technology, such as telephone communications, is not available in a heavily damaged area.

The other type is a ‘social network’, which represents social relationships among people. This is more common than the physical network because the information transmission occurs via various media of communication. In addition, if the long-term dynamics are examined, face-to-face communications can also form the social network because travel times will not constrain people’s ability to meet up with each other.

The structure of physical networks, which should be similar to that of transport networks, is assumed to be a one-dimensional lattice network. The lattice network is a network in which links are wired between two nodes that are geometrically near each other. For example, if each node is connected to the four nearest nodes, the configuration of the network becomes a ring, as shown in Fig. 4. The physical network in which $2m$ nearest nodes are connected to each node is denoted by $L(m)$. The mean distance of $L(m)$, denoted by $\bar{d}_P(m)$, is (Vega-Redondo, 2007)

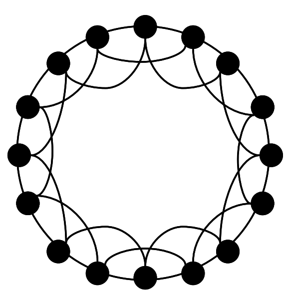

Fig. 4: Example of the lattice network, n = 16 and m = 2.

$$\bar{d}_P(m) = \frac{1}{2} + \frac{n-1}{4m}, \tag{53}$$

which implies that $\bar{d}_P(m)$ increases linearly with respect to the number of travellers. If one is interested in two-dimensional networks, a two-dimensional lattice network can also be employed, the mean distance of which is approximately proportional to $\sqrt{n}$. These results indicate that the mean distance depends on the number of travellers in the society—it can be very large if many travellers exist. The number of neighbour travellers $\bar{N}$ in $L(m)$ is $2m$ for all travellers.

The most well-known characteristic of social networks is the 'small-world' phenomenon, in which the distance between two arbitrary nodes is generally short. Starting with the famous experiment performed by Milgram (1967), several studies have revealed that the mean distance of social networks in the real world is generally small, i.e., less than 10 (see Jackson (2008) for a review of the empirical works). This implies that the mean distance in social networks, denoted by $\bar{d}_S$, can be simply approximated by

$$\mathrm{Ord}\left(\bar{d}_S\right) \approx 1 \sim 2, \tag{54}$$

regardless of the detailed structure of the networks.

A characteristic known as 'scale-freeness' is also a well-known property of the number of neighbours. In scale-free networks, the degree of nodes (i.e., the number of links attached to each node) is widely distributed, which often leads to a power distribution that has a fat-tailed property (Barabási and Albert, 1999). There is no particular characteristic related to the value of $\bar{N}$ in social networks, but the values reported in the literature are not very large. For example, Barabási and Albert (1999) demonstrated cases in which $\bar{N} = 28.78, 5.46,$ and 2.67, whereas Jackson (2008) reviewed cases in which $\bar{N}$ varies from 1.7 to 15.5. Considering these values found in the literature, we employ a simple assumption, that is,

$$\mathrm{Ord}\left(\bar{N}\right) \approx 1 \sim 2, \tag{55}$$

in the following analysis.

Proposition 2 is reviewed using the above characteristics. First, consider the physical networks. Because $\bar{d} \sim 1$ is basically not satisfied in larger networks, Proposition 2 will not hold and, consequently, the existence of the intentional search has no effect related to transmitting information across the society. On the other hand, in social networks, $\bar{d} \sim 1$ is likely to occur and, consequently, there is a chance that the existence of the intentional search will allow travellers to make efficient choices, unless lock-in behaviour arises owing to rapid diffusion of information.

4. Numerical test

To confirm the results of the mathematical analyses in the previous section, results of numerical tests are provided in this section. In the numerical tests, three types of networks were considered. The first was a lattice network $L(1)$. The second was a scale-free network that was generated with the algorithm proposed by Barabási and Albert (1999), denoted by *SF*. The third was another type of social network proposed by Watts and Strogatz (1998), where $p = 0.8$ and $k = 8$ were employed in the algorithm proposed in this paper. Networks of this type have a small-world property, but they do not have the scale-free property. This type of network, denoted by *SW*, was employed for the purposes of comparison with the scale-free network. The number of nodes is 1000 for all network types. Ten SF networks and ten SW networks were generated randomly. The utilities of the alternatives are set as $v_H = 2000$ and $v_L = 1000$, which lead to $v_+ = 3000$, $v_- = 1000$, and $v_+ / v_- = 3$. The speed of decision making (r) was fixed to 1. To estimate the theoretical bandwidth of information diffusion speed ($\gamma / \bar{d} = 1/u$) in which the efficient choices of travellers are estimated, the conditions stated in Section 3.2 was examined by assuming $\varepsilon = 1$ as follows:

Condition 1: If $0.001 < 1/u \le 0.002$, $1/995 \sim 0.001 < 1/u$ must be established.
Condition 2: If $0.002 < 1/u \le 0.003$, $1/u < 0.25$ must be established.
Condition 3: If $0.003 < 1/u$, $1/u < 1000/2004 \sim 0.5$ must be established.

Combining these conditions, the theoretical bandwidth of $\gamma / \bar{d}$ was calculated as $0.001 < \gamma / \bar{d} < 0.5$. The characteristics of the network are shown in Table 1, where those of *SF* and *SW* are the averaged values of the randomly generated networks. Fig. 5 depicts the structures of $L(1)$, *SF*, and *SW*, but the number of nodes is set to 50 in these figures to maintain readability. It can be seen that *SW* has a structure that is denser than those of the other two types.

A Monte Carlo simulation was performed to calculate the proportion of travellers who select *H*. For each sample of network *SF* and *SW*, 100 calculations were made, and the proportion of travellers selecting *H* was counted at the end of each run. Thus, 1000 samples were taken in total for both *SF* and *SW*. A total of 1000 calculations were also made for $L(1)$. These calculations were made for several γ (ranging from 0.0001 to 10000) with $\delta_{IS} = 0$ (without intentional search) and $\delta_{IS} = 1$ (with intentional search).

The results are shown in Figs. 6 to 11. The figures showing the results without intentional search also indicate the theoretical bandwidth of $\gamma / \bar{d}$ where the efficient choices of travellers are expected. This is also given in Table 1. Each graph shows the relationship between $\gamma / \bar{d}$ and the mean (indicated by circles) and standard deviation (indicated by error bars) of the proportion of travellers selecting *H* at each run of the simulation with the same $\gamma / \bar{d}$.

Table 1: Parameters of the networks in the numerical test

Type of Network	Scale Free: *SF*	Small World: *SW*	Lattice: $L(1)$
Number of Nodes n	1000	1000	1000
Mean Distance $\bar{d}$	7.17	3.57	250.25
Mean Degree of Nodes $\bar{N}$	1.998	8	2
Lower Limit of $\gamma / \bar{d}$ for the efficient choices	0.001	0.001	0.001
Upper Limit of $\gamma / \bar{d}$ for the efficient choices	0.5	0.5	0.5

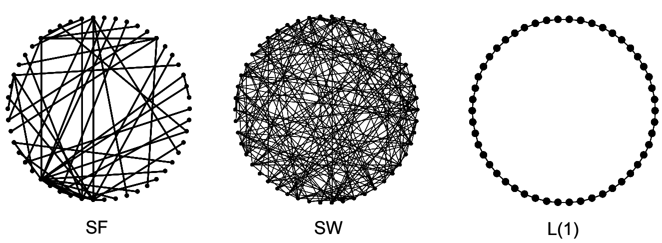

Fig. 5: Structure of three network types, where n = 50.

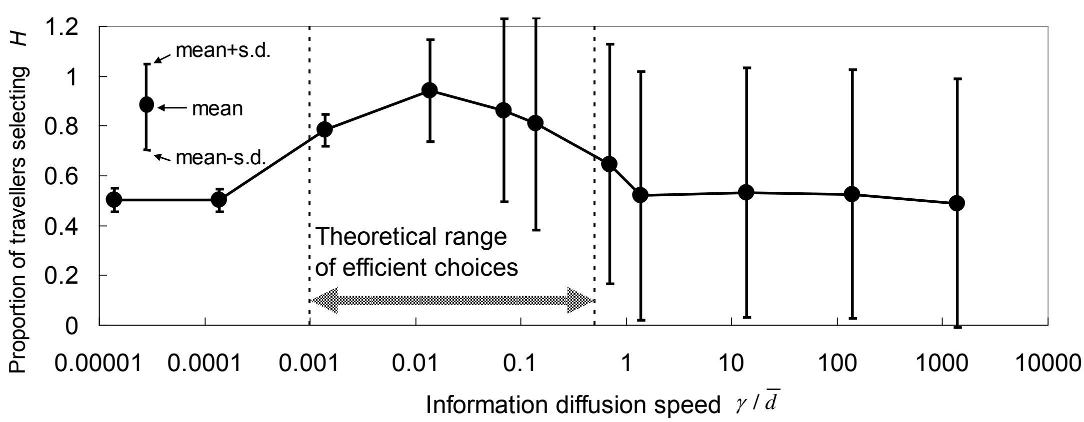

Fig. 6: Proportion of travellers selecting alternative *H*; network = *SF*, without intentional search.

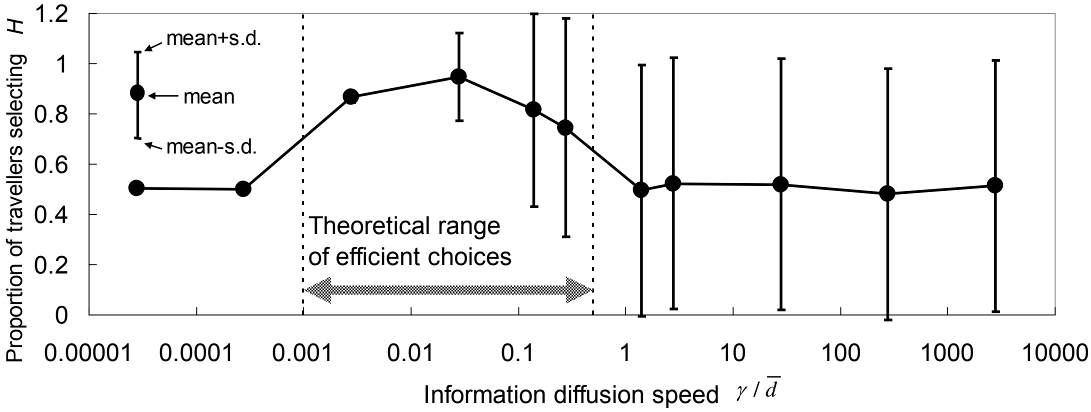

Fig. 7: Proportion of travellers selecting alternative *H*; network = *SW*, without intentional search.

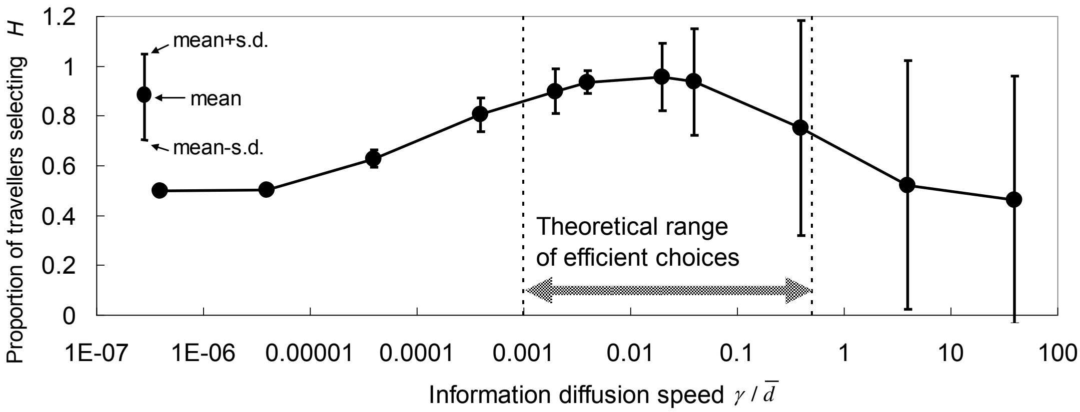

Fig. 8: Proportion of travellers selecting alternative *H*; network = *L*(1), without intentional search.

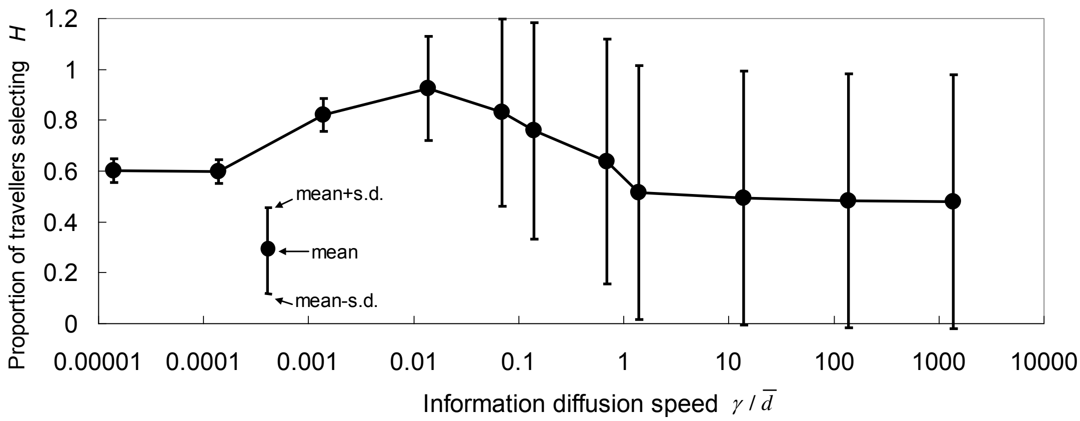

Fig. 9: Proportion of travellers selecting alternative *H*; network = *SF*, with intentional search.

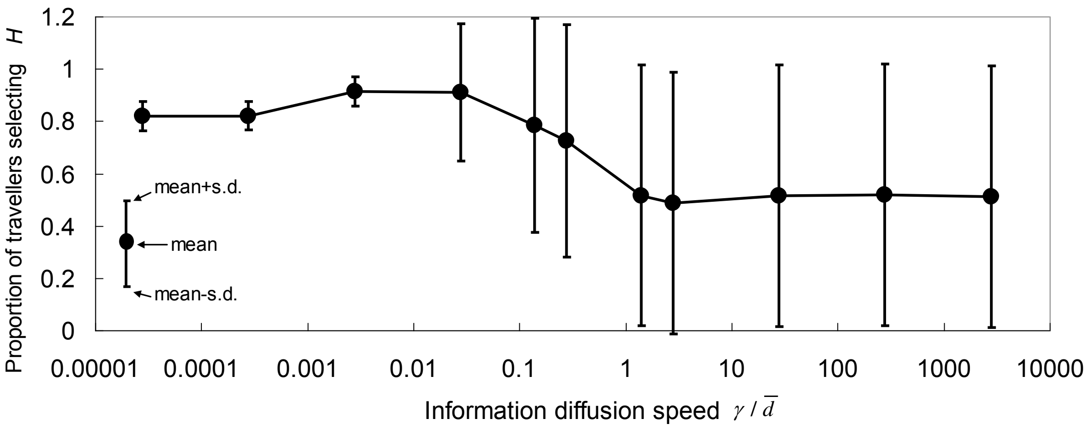

Fig. 10: Proportion of travellers selecting alternative *H*; network = *SW*, with intentional search.

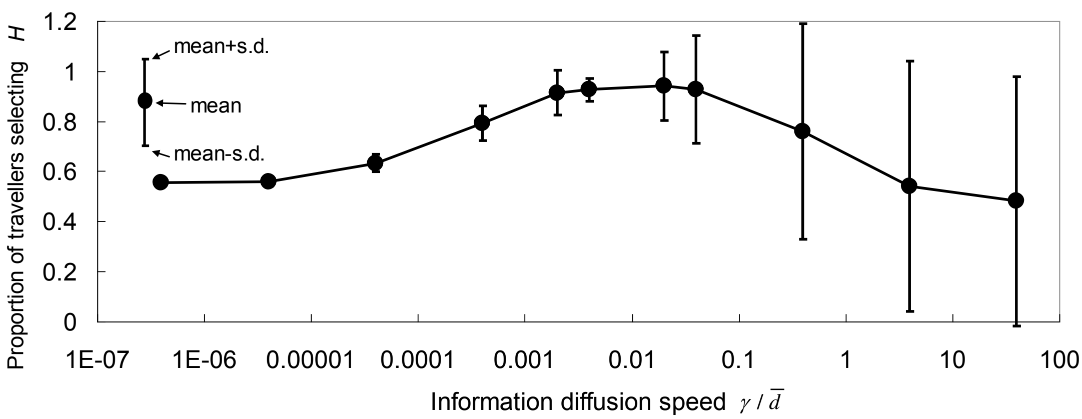

Fig. 11: Proportion of travellers selecting alternative *H*; network = *L*(1), with intentional search.

Figs. 6 to 11 have a common characteristic in the range of larger $\gamma / \bar{d}$ (especially $\gamma / \bar{d} > 1$), that is, the proportion of travellers selecting *H* is around 50% on the average, but the standard deviation is very high. This result shows that the lock-in phenomenon occurs when information diffuses at higher speeds. To confirm the presence of the lock-in phenomenon, Fig. 12 depicts distributions of the number of travellers selecting *H* for a few selected cases of network *SF*. It can be seen in Fig. 12 that the distributions have two peaks where $\gamma / \bar{d} = 1.4$, implying that the dynamics exhibit lock-in behaviour with higher speeds of information diffusion, as expected from the analysis in Section 3.1.

Another common characteristic found in these results is that travellers make random choices in the range of smaller $\gamma / \bar{d}$ (especially $\gamma / \bar{d} < 0.0001$). In this region, the proportion of travellers selecting *H* is also 50%, but the standard deviation is quite small. This implies that the travellers' decisions have no correlation as a result of the lack of information transmission.

On the other hand, each graph contains a range of $\gamma / \bar{d}$ in which the proportion of travellers selecting *H* is substantially greater than 0.5, implying that most travellers were able to make the efficient choice (i.e., selecting *H*) during the dynamics. To check whether the numerical results can be explained by the theoretical prediction, Figs. 6,

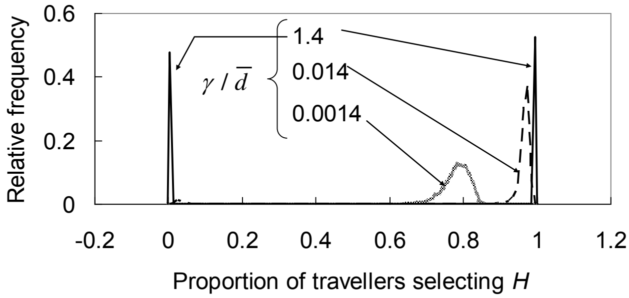

Fig. 12: Distribution of the proportion of travellers selecting *H* in the *SF* network without intentional search.

7, and 8 include the theoretical prediction of the range of the efficient choices (that is, $0.001 \le \gamma / \bar{d} \le 0.5$) in the graph. It can be observed that the theoretical prediction agrees well with the results of the numerical calculations. Although the lock-in phenomenon seems to occur in the faster region of the efficient choices, the probability of locking in to alternative *H* is substantially greater than 50%, meaning that the travellers are still likely to make efficient choices in this region.

As predicted in Section 3.3, the effect of intentional searching appears only in the case in which the mean distance $\bar{d}$ is short, that is, it appears only in the case of *SW*, where $\bar{d} = 3.57$. As shown in Fig. 10, the proportion of travellers selecting *H* is higher (~0.8), even in the range of slower information diffusion speeds, implying that the information diffuses in the network at a certain speed due to the intentional searching. On the other hand, in the case of *SF*, where $\bar{d} = 7.17$, this effect is fairly small, as shown in Fig. 9. These results imply that there is a fairly small range of $\bar{d}$ for performing effective distributions of information by intentional searches.

Apart from $\bar{d}$, the difference of network structure between the *SF* network and the *SW* network is not apparent. Indeed, the graphs shown in Figs. 6 and 7 are quite similar. On the other hand, the results of *L*(1) exhibit different characteristics than do those of *SF* and *SW* in the region of slower information diffusion speeds. In *SF* and *SW*, travellers' decisions are completely random for $\gamma / \bar{d} = 0.0001$, whereas around 60% of travellers select *H* in *L*(1) for the same speed. This result may be caused by the difference in the network structure—in the lattice networks, the number of nodes gradually increases with respect to the distance, whereas it rapidly increases in networks with the small-world property. Therefore, it can be expected in the case of the *L*(1) network that information is gradually diffused over a part of the network, even when the information diffusion speed is much slower than the theoretical lower limit for maintaining efficient choices.

Overall, it can be concluded that Propositions 1 and 2, which were derived from the theoretical analysis, are supported by the numerical test. This implies that these propositions can be employed to assess the travellers' behaviour in the proposed model in various cases.

5. Conclusions and discussions

This study proposed a model that describes travellers' choice behaviour when the choices are non-recurrent and the only available information about the alternatives is based on other travellers' experiences and is transmitted only via the information transmission network. The characteristics of the model were mathematically analysed to find the conditions in which information about the better alternatives is well distributed among travellers and helps them to make efficient choices. The results of the analysis revealed that the ratio of the information diffusion speed to the decision-making speed must be approximately between the inverse of the number of nodes (1/*n*) and a value that is derived from the utilities of both alternatives. It was also revealed that, in the information transmission networks with mean distance $\bar{d} \approx 1$, travellers' intentional searching made at the time of their decisions can effectively distribute information if no rapid incidental distribution of information exists. These results were confirmed by the numerical test as well as the mathematical analysis.

The results of this study have two important implications regarding policies of information transmission for non-recurrent travel behaviours. First, there is an appropriate range of information diffusion speeds that achieve efficient choices. It is easy to imagine that excessively slow diffusion does not help travellers obtain appropriate information, but rapid distribution is also harmful—it seems somewhat contradictory that accelerating the information diffusion can result in a lack of appropriate information about a better alternative. Second, the intentional search can help the travellers to make efficient choices if a strong small-world property exists in the information transmission network and no rapid information diffusion exists. Although this condition is rather severe, a simple policy can be adopted if the small-world property exists—a policy that suppresses the rapid diffusion of information. Of course, policies that restrict the exchange of information among people are not realistic; consequently, this suppression should be made by more sophisticated mechanisms through the market system. For example, if any useful or reliable information can have an appropriate price in the market, people may tend to avoid unnecessary transmissions of information unless they demand it for making decisions.

Although the proposed model only describes the abstract situation of non-recurrent travel behaviour, its implications can be applied in a wide variety of transport studies involving non-recurrent choice problems. For example, consider evacuation behaviour after a major disaster. If information is transmitted only via primitive media such as face-to-face talking, information transmission is quite slow, and the recovery of efficient communication tools, such as mobile phone networks or radio broadcasts, is required. However, once the communication tools are recovered at a certain level, their improvement is no longer necessary, or it may even be harmful, because it accelerates the diffusion of information, which leads to lock-in behaviour and, consequently, the unnecessary (and even dangerous) congestion created by evacuees rushing into one destination or route. Instead, a policy that collects true information and injects it into the information transmission network externally is more likely to avoid lock-in behaviour, if such an information source is available (e.g., effective escape directions in a building). The implications of the model may also be applied to long-term decisions, such as residential choices or car ownership behaviour, as well as to destination choices related to overseas travelling. In such long-term situations, rapid incidental diffusion may be unavoidable; consequently, increasing the quality of the intentional searches may improve the situation if the information transmission network possesses the small-world property.

Of course, one should construct a detailed model or simulation to evaluate a particular situation precisely; however, the proposed model should be helpful in making forecasts or theoretical explanations regarding the qualitative characteristics of the detailed models before the complicated calculations are carried out.

Several expansions of the proposed model in future studies will now be pointed out. First, this model assumed uniform distribution to explain the timings of travellers' decisions; however, various distributions can be considered to explain the decision timings. A famous model for explaining the timings of decisions, proposed by Bass (1969), modelled timings of the initial purchase of new products and showed that the rate of decision making grows from an initial stage and peaks at a certain time. Such a mechanism explaining the timings of decision making should be incorporated in the proposed model to assess the effect caused by the mechanism. The multinomial choice problem is also a theoretical concern. It would be valuable to consider how the flow of information can be regulated by the public sector to improve public welfare, or how people or organisations (e.g., advertising agents) having an interest in the results of travellers' choices try to interfere with the information transmissions. Incorporating the change of populations and cohort effects due to aging and births is also important when the long-term situation is considered.

In addition to model expansions, empirical examinations of the model are important. However, it should be pointed out that collecting data from the real world can be difficult because unknown alternatives cannot be detected by observers when lock-in occurs. Investigating the case of a disaster seems to be easier because constructing an artificial evacuation situation is not very difficult and has already been carried out in several existing studies (e.g., Nilsson and Johansson, 2009). Other empirical approaches may be accomplished by preparing artificial alternatives that are selected by respondents who are connected to each other by social networks; however, preparing a well-controlled situation whose social relationships are well known seems to be a challenging task.

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Appendix A. Calculation of the delay differential equation (Eqn. (44))

First, $\Delta(t)$ between ε / r and $u+\varepsilon / r$ can be calculated by integrating the equation

$$\frac{d\Delta}{dt}=\frac{v\_r}{2}, \tag{56}$$

which can be obtained by substituting $\Delta(t)=0$ into Eqn. (44). Therefore,

$$\Delta(t)=\frac{v\_r}{2}\left(t-\frac{\varepsilon}{r}\right)-v_L\varepsilon \tag{57}$$

for $\varepsilon / r \le t \le u+\varepsilon / r$ by assuming $\Delta(t)=0$ for *t* with $t<\varepsilon / r$. Similarly, for $u+\varepsilon / r \le t \le 2u+\varepsilon / r$,

$$\Delta(t)=\Delta\left(u+\frac{\varepsilon}{r}\right)+\int_{\varepsilon/r}^{t-u}\left\{\frac{v_+r}{4}\Delta(s)+\frac{v\_r}{2}\right\}\mathrm{d}s, \tag{58}$$

and hence,

$$\Delta(t)=\Delta\left(iu+\frac{\varepsilon}{r}\right)+\int_{(i-1)u+\varepsilon/r}^{t-u}\left\{\frac{v_+r}{4}\Delta(s)+\frac{v\_r}{2}\right\}\mathrm{d}s \tag{59}$$

for $iu+\varepsilon / r \le t \le (i+1)u+\varepsilon / r$. Thus, using the area of a rectangle to approximate the area calculated by the integral, we obtain

$$\Delta\left((i+1)u+\frac{\varepsilon}{r}\right)-\Delta\left(iu+\frac{\varepsilon}{r}\right)\left(\frac{v_+ru}{4}+1\right)-\frac{v\_ru}{2}=0. \tag{60}$$

This is a first-order difference equation. From (57), the initial condition of this difference equation is:

$$\Delta\left(u+\frac{\varepsilon}{r}\right)=\frac{v\_ru}{2}-v_L\varepsilon, \tag{61}$$

which derives the solution of (60), as shown in Eqn. (45).